Capacitated lot-size production planning in process industry

Selen, W.J.; Heuts, R.M.J.

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TILBURG UNIVERSITY
KATHOLIEKE UNIVERSITEIT BRABANT
POSTBOX 90153
5000 LE TILBURG
THE NETHERLANDS

[redacted]

DEPARTMENT OF ECONOMICS

RESEARCH MEMORANDUM

CAPACITATED LOT-SIZE PRODUCTION PLANNING PROCESS INDUSTRY

Willem Selen
Ruud M. Heuts

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Process Industry

by

Willem Selen

Ruud M.Heuts

Department of Econometrics

Faculty of Economics

Tilburg University

P.O. Box 90153

The Netherlands

Phone: (31)-13-662176

(31)-13-662352

1. Introduction

In the production planning of a batch production process, a problem of considerable interest is the determination of lot sizes for multiple products to be produced on a single bottleneck facility. This production environment is often encountered in the process industry, such as the manufacturing of plastics. The capacitated lot size problem can be formulated as [9] :

$$\text{Min} \quad \sum_{t=1}^{H} \left\{ \sum_{i=1}^{N} \left\{ S_i \delta(X_{i,t}) + h_i I_{i,t} \right\} \right\}$$

s.t.

$$I_{i,t-1} + X_{i,t} - d_{i,t} = I_{i,t} \qquad i \in N,\ t \in T$$

$$\sum_{i=1}^{N} a_i X_{i,t} \leq C_t \qquad t \in T$$

$$I_{i,0} = I_{i,H} = 0 \qquad i \in N$$

$$X_{i,t},\ I_{i,t} \geq 0 \qquad i \in N,\ t \in T$$

$$\delta(X_{i,t}) = 1 \text{ if } X_{i,t} > 0,\ 0 \text{ otherwise} \qquad i \in N,\ t \in T$$

where

N= the index set of products

T= the index set of periods

H= the time horizon

S_i= setup cost for product i

h_i= holding cost per unit per period for product i

$d_{i,t}$= requirement of product i in period t

a_i= production time per unit for product i

C_t= capacity available in period t

with decision variables:

$X_{i,t}$= lot size of product i in period t

$I_{i,t}$= inventory of i at the end of period t

$\delta(X_{i,t})$= binary decision variable indicating whether or not product i is setup in period t or not

This problem can be classified as NP-hard and an optimal solution within reasonable computer time is not available so far [7,9]. However, the literature is abundant with heuristic approaches to lotsizing under capacity constraints in a single stage production system [1,3,4,6,10,11,12,16]. An excellent review paper is presented by van Wassenhove and Maes[18]. Many heuristics deal with the capacitated lot size (CLSP) problem as was defined earlier, where there is only a single resource constraint and where setups do not consume limited resources. Furthermore, setups are assumed to be solely product-dependent and not sequence-dependent. In fact, sequencing decisions within each period are not being considered in the simple CLSP. As such, a "feasible solution" may still cause problems since on the detailed level resource requirements may interfere. In their review paper, van Wassenhove en Maes point out that all "single resource" heuristics that were investigated exploit the above mentioned simplifications to a great extent and that" they cannot be directly applied to more realistic cases (e.g. several resources, time-variable capacity absorption, etc). Adjustments are very difficult to make and in fact would in most cases completely alter the heuristic. This, of course, considerably reduces the usefulness of single resource heuristics in practice"[18]. Besides single resource heuristics, which assume that setups do not require the single limited resource, more general mathematical programming based heuristics comprising set covering type methods and Lagrangean relaxation heuristics, have been developed [1,2,5,14,15,16,17]. However, for this last group of heuristics very few computational results are available for capacitated dynamic lotsizing problems, making it difficult to fully assess their behaviour and computational requirements[18]. It is the purpose of this research to develop a new heuristic, based in part on a recent single resource heuristic by Gunther[9], that handles all the simplifications that have been traditionally imposed and allows for implementation in a more complex process industry setting. The production environment in which the new heuristic will be developed, is discussed next.

2.Production setting

The process industry often has to deal with capacitated lot sizing problems when processing multiple products on a single bottleneck facility. An example is Dow Chemical at Terneuzen, The Netherlands, where seven chemical products (latex) are manufactured on the same production facility, consisting of a reactor, degasser,stripper, cooler, and various filters and storage tanks. In this particular case the stripper makes up the bottleneck of the production process Single resource heuristics cannot be considered for lot-sizing because of the following:

- setups require a substantial portion of the available production capacity per shift

- setup costs are highly sequence-dependent and as such one cannot assign a single setup estimate to a particular product

- production capacity is not only determined by the stripper(bottle-neck) capacity, but also by the storage tank capacity assigned to the product of interest.

- production occurs as a "batch-process" of a fixed number of tons, being the reactor volume. In order to achieve the necessary chemical reactions it is essential that the reactor is completely filled each time a production lot is run. As demand is ussually not a multiple of the batch-size, excess inventories will accumulate, which in turn will affect subsequent lot-sizes and storage capacities.

It is clear that this process is harder to formulate and would not lend itself to mathematical programming approaches, moreover as the storage capacity for a particular product would be a variable in itself, varying over time, depending on previous inventories and up-to-then established lot sizes. As the single resource heuristic by Gunther provides the basis for the simplified CLSP and proved to be computationally very efficient, it is used in part as the underlying framework from which the new heuristic will be developed.

3. The heuristic

3.1 Key concepts

- Setups consume regular production capacity.
- Sequence-dependent setup costs will be incorporated based on a cost-

savings function showing the average savings in switch-over cost when adding future requirements of a particular product to an existing lot-size.

- Using a "maximum capacity overload"-principle, similar to Gunther's [9], balancing future overcapacity by pre-production in earlier periods, allows for shifting of production requirements over multiple periods instead of being restricted to a "period by period"approach.In addition, as compared to Gunther, our approach allows for shifting fractional requirements instead of being restricted to shifting entire requirements at once.
- Feasibility of planned lot-sizes is guaranteed by matching planned production quantities to existing storage capacities in a particular planning period.

- The heuristic deals with the added complexity of a batch production process.

- The procedure assumes that storage tanks have "a priori" been assigned to the various products to be manufactured. However, alternate tank assignments could easily be incorporated in the analysis by altering the storage capacity parameters per product.

3.2 Notation

The notation that will be used is presented alphabetically as follows:

a_i = production time (in hours) needed to produce 1 batch of product i;

$i=1,\ldots.,n$

a_{ij} = switch-over time (in hours) from product i to product j

$a_{ip(i)}$ = average switch-over time to product i(in hours) in period p(i)

a_{wt} = worst average switch-over time in period t

b_{io} = starting inventory for product i at the beginning of period 1

BI_{it} = beginning inventory of product i at the beginning of period t

d_{it} = demand for product i in period t, accumulated at the end of period t (in tons)

H = last period of planning horizon

k = current period of production

n = number of products for which there is demand during the planning period

N = set containing all products 1,....,n

N_k^* = subset of product set N,containing all products with positive net requirements in subsequent periods p(i)>k

PC_t = nominal production capacity in period t (in hours), based upon a $(100-\alpha)$% capacity level

PCH_t = production capacity at hand (in hours) for shifting requirements in period t to reference period k for pre-production in period k, taking into account reserved production capacity to balance future over-capacity in the system

PCO_t = production-overcapacity in period t with reference to current period of production k

$PCS_{ip(i)k}$ = potential average cost savings (in hours) for pre-producing future requirements of product i in period p(i), in the current production period k

S_t = collection of all possible production schedules in period t for products to be produced in period t

$[S_t]$ = subset of S_t, being the collection of schedules where the product scheduled in the first position matches the product scheduled in the last position of the schedule chosen for period t-1

SPC_t = slack production capacity (in hours) in period t

STC_{it} = slack tank capacity of product i (in tons) at the beginning of period t

t = time unit for planned production (in weeks), t=1,....,H

TC_{it} = nominal tank capacity of product i in period t (in tons)

TC_{wit} = adjusted (workable) tank capacity for product i in period t to be used in the production planning process, that incorporates a buffer of one batchsize allowing for batch (discrete) production. In other words, the buffer allows for rounding continuous production quantities to the next higher integer (lot-size)

X_{it} = net requirements of product i in period t (in batches)

$ya_{ip(i)k}$ = added continuous production quantity (in batches) of product i from future period p(i) to scheduled production of product i in reference period k

y_{ik} = scheduled production quantity (in batches) of product i in period k, not being restricted to discrete lot-sizes

y_{ik}^{final} = final lot-size (in batches) of product i to be produced in period k

3.3 Structural equations

$a_{wt} = \Big\{$ longest switch-over time (in hours) among possible switch-over times of schedules $\in S_t \Big\} \Big/ \Big\{$(number of products with positive requirements in period t) - 1 $\Big\}$

Note: The a_{wt}-concept is used to provide a conservative estimate of switch-over time during a particular production period t, which would result in a conservative slack production capacity estimate for period t. However, it is possible that the product scheduled in the last position for production in period t-1 is not produced in period t. As such, an additional switch-over between schedules of subsequent time periods t-1,t will be incurred. This situation will not be explicitly modelled as the a_{wt} measure already provides a conservative etstimate and it is unlikely that this single additional switch-over would cause infeasibilities in available slack production capacity.

$$SPC_t = PC_t - \sum_{i=1}^{n} a_i y_{it} - a_{wt} \qquad t=k,\ldots\ldots,H$$

$$PCO_t = \max\left\{0, \max_{\tau=k+1,t} \left(\sum_{j=k+1}^{\tau} - SPC_j\right)\right\} \qquad t=k+1,\ldots,H$$

$$PCH_t = SPC_k - PCO_{t-1} \qquad \text{with } PCO_k=0 \qquad t=k+1,\ldots\ldots,H$$

$$TC_{wit} = TC_{it} - \text{batchsize} \qquad \begin{cases} t=1,\ldots\ldots,H \\ i=1,\ldots\ldots,n \end{cases}$$

$$BI_{it} = \begin{cases} b_{io} & \text{for } t=1;\ i=1,\ldots,n \\ BI_{it-1} + \text{batchsize} * y_{it-1}^{final} - d_{it-1} & \text{for } t=2,\ldots,H-1;\ i=1,\ldots,n \end{cases}$$

$$STC_{it} = TC_{wit} - (BI_{it} + \text{batchsize} * y_{it}) \qquad \text{for } t=1,\ldots,H-1;\ i=1,\ldots,n$$

Note:

For $STC_{it} < 0$ because of rounding to discrete lot-sizes,

set $STC_{it} = 0$.

$$\bar{a}_{ip(i)} = \frac{\sum_{j \neq i}^{n} a_{ij}}{n - \varepsilon_{p(i)} - 1}$$ where $\varepsilon_{p(i)}$ = number of products with zero net requirements in period $p(i)$

$$ya_{ip(i)k} = \min \left\{ X_{ip(i)} , \frac{PCH_{p(i)}}{a_i} , \frac{STC_{ik}}{batchsize} \right\}$$

$$PCS_{ip(i)k} = \left\{ \lceil y_{ik} \rceil + \lceil ya_{ip(i)k} \rceil - \lceil y_{ik} + ya_{ip(i)k} \rceil \right\} * \bar{a}_{ip(i)}$$

where $\lceil\ \rceil$ stands for rounding up to the next integer value

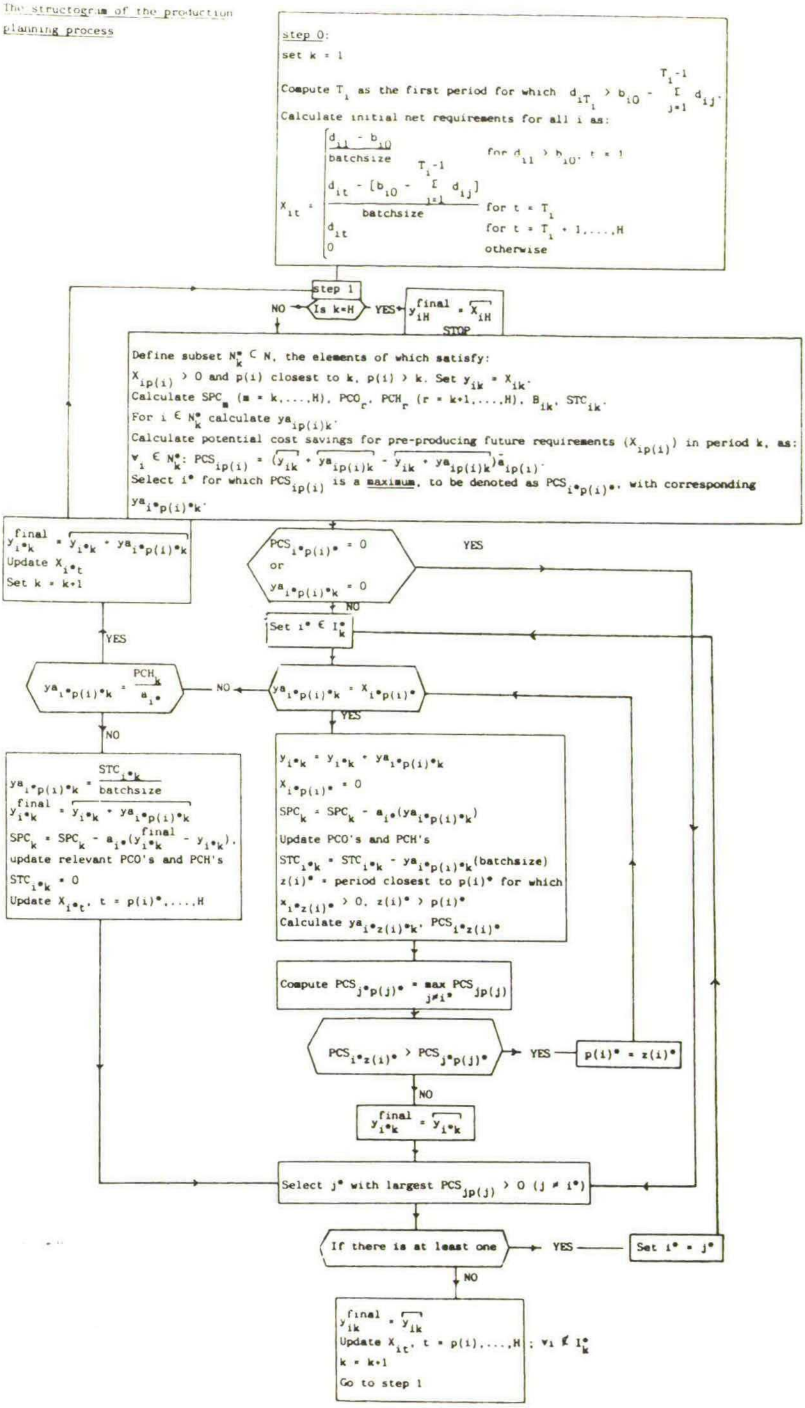
I_k^* = collection of products selected for pre-production in period k

$$\text{updated } X_{it} = \begin{cases} X_{it} - (y_{ik}^{final} - y_{ik}) & \text{for } t=p(i) \text{ and } X_{ip(i)} > y_{ik}^{final} - y_{ik} \\ X_{iT_i} - \left[(y_{ik}^{final} - y_{ik}) - \sum_{j=p(i)}^{T_i - 1} X_{ij} \right] & t=T_i \text{ and } \\ & T_i \text{ is the first period for} \\ & \text{which } X_{iT_i} > (y_{ik}^{final} - y_{ik}) - \sum_{j=p(i)}^{T_i - 1} X_{ij} \\ X_{it} & t= T_i+1,\ldots,H \\ 0 & \text{otherwise} \end{cases}$$

3.4 Structogram of the production planning heuristic

For a particular production period, determine regular production needed on a lot-for-lot basis of the net requirements for that period.
Based upon potential cost savings, a product is selected for pre-production in the current production period. This quantity to be pre-produced is determined by the net requirements in the period from which shifting occurs, the available remaining production capacity at hand in the current production period, as well as the available slack tank capacity left for the product to be pre-produced. This process of adding future requirements to the current production load will continue as long it results in additional cost savings and the feasibility of the production and tank capacities is not violated. This adding process is based on continuous lot-sizing. The production quantities obtained under this process are eventually rounded up to the next integer value, leading to feasible, discrete lot-sizes (batches). Feasibility of the final schedule is guaranteed as a safety factor of α % in production capacity together with a conservative switch-over time estimate is incorporated in the analysis.
Furthermore, the workable tank capacities include a buffer of one batchsize to allow for the rounding process described earlier.
Details of the structogram of the production planning heuristic are given in the following flow-chart.

The structogram of the production planning process



3.5 The production scheduling process

After final production quantities are determined by means of the production planning heuristic, efficient production schedules for each production period are selected as follows:
Define the scheduling set for period j as

$$S_j = \left\{ \text{all possible schedules for product i with } y_{ij}^{final} > 0 \right\}$$

Furthermore, define the subset $[S_k] \subset S_k$ as the collection of schedules where the product scheduled in the first position matches the product scheduled in the last position of the schedule chosen for period k-1.

A) Schedule for period 1,2 :

Determine S_1.

Determine $[S_2]$ for every schedule of S_1 and compute the total switch-over time. Select the starting schedule for which the total switch-over time is minimized. As such, the schedules for periods 1 and 2 are determined simultaneously.

B) Schedule for period 3,...., H:

Given the starting schedule determined in A, the schedule for period 2 is determined as well.

Set k=3

Step 1

k=H+1 — Yes → Stop

No

Determine [S_k]. When [S_k] = $\emptyset$, go to step 3

Step 2

Compute for every schedule of [S_k] the total switch-over time and select the schedule for period k as the one with the smallest switch-over time.

Set k=k+1

Return to step 1

Step 3

Given the product scheduled in the last position in the production schedule for period k-1, determine S_k and select the schedule for which total switch-over time, including switching from the product scheduled in the last podition in k-1 to the product scheduled in the first position in k, is minimized.

Set k=k+1

Return to step 1.

The logic behind this scheduling procedure is that it would be very difficult, if not impossible, to evaluate all possible production schedules for every period in the planning horizon. Moreover, given the continuous nature of the production process, it would not be efficient to schedule the same product more than once within a particular production period. This would call for splitting a particular lot-size into multiple parts, causing unnecessary additional switch-over time. Futhermore, by "matching" the product scheduled in the last position of the schedule of the previous period to the product scheduled in the first position of the current period, one would avoid the same product to be scheduled more than once in a particular production period and save an additional switch-over. As is indicated in the above procedure, a modified approach will be taken when production cannot be continued into the subsequent production period in this fashion for the case where the product scheduled in the last position in the previous period is not up for production in the current period (see step 3).

Next, the procedures described above will be illustrated by means of a simple numerical example based in part on real industry data.

4. Numerical example

4.1 Data

Demand (in batches):

product i	week t: 1	2	3	4
1	5.88	6	9	5.9
2	6.41	5	10	7.2
3	0.9	1.5	7	0.5

Switch-over time matrix (in hours):

	1	2	3
1	-	0.83	4
2	2.99	-	4
3	4	4	-

Product i	production batch time (in hours)	tank capacity p.week (in tons)	starting inventory (in tons)	batchsize (in tons)
1	5.25	600	50	55
2	5.8	600	60	55
3	8.5	500	11	55

Production capacity per week is given as 168 hours at 100% capacity(α=0).

4.2 The production planning process

step 0 : k=1

initial net-requirements, X_{it} :

	1	2	3	4
1	4.97	6	9	5.9
2	5.32	5	10	7.2
3	0.7	1.5	7	0.5

step $k=1 \neq H=4$

$N_1^* = \{1,2,3\}$

$y_{11} = 4.97$, $y_{21} = 5.32$, $y_{31} = 0.7$

$SPC_1 = 97.1$, $SPC_2 = 86.75$, $SPC_3 = -4.75$, $SPC_4 = 83.02$

$PCO_2 = 0$, $PCO_3 = 0$, $PCO_4 = 0$, $PCH_2 = 97.1$, $PCH_3 = 97.1$, $PCH_4=97.1$

$BI_{11} = 50$, $BI_{21} = 60$, $BI_{31} = 11$

$STC_{11} = 221.65$, $STC_{21} = 192.4$, $STC_{31} = 395.5$

$ya_{121} = 4.03$, $ya_{221} = 3.5$, $ya_{321} = 1.5$

$PCS_{12} = 3.5$, $PCS_{22} = 0$, $PCS_{32} = 0$

$i^* = 1$

$I_1^* = \{1\}$

$ya_{121} = STC_{11} / 55$

$$y_{11}^{final} = \lceil y_{11} + ya_{121} \rceil = \lceil 4.97 + 4.03 \rceil = 9$$

$$SPC_1 = SPC_1 - a_1 \, (y_{11}^{final} - y_{11}) = 75.94$$

$PCO_2 = PCO_3 = PCO_4 = 0$, $PCH_2 = PCH_3 = PCH_4 = 75.94$

$STC_{11} = 0$

Updated X_{1t} : $X_{12} = 1.97$, $X_{13} = 9$, $X_{14} = 5.9$

no j^* with $PCS_{jp(j)} > 0$ as $PCS_{22} = PCS_{32} = 0$

$y_{21}^{final} = y_{21} = 5.32 = 6$

$y_{31}^{final} = y_{31} = 0.7 = 1$

Updated remaining net-requirements X_{it}, $i \notin I_1^*$

	week		
	2	3	4
i=2	4.32	10	7.2
i=3	1.2	7	0.5

k=2, return to step 1

k=2≠ H=4

$N_2^* = \{1,2,3\}$

$y_{12} = 1.97$, $y_{22} = 4.32$, $y_{32} = 1.2$

$SPC_2 = 114.4$, $SPC_3 = -4.75$, $SPC_4 = 83.02$

$PCO_3 = 4.75$, $PCO_4 = 0$, $PCH_3 = 114.4$, $PCH_4 = 109.65$

$BI_{12} = 221.6$, $BI_{22} = 37.45$, $BI_{32} = 16.5$

$STC_{12} = 215.05$, $STC_{22} = 269.95$, $STC_{32} = 362.5$

$ya_{132} = 3.91$, $ya_{332} = 4.91$, $ya_{332} = 6.59$

$PCS_{13} = 0$, $PCS_{23} = 0$, $PCS_{33} = 4$

$i^* = 3$

$I_2^* = \{3\}$

$ya_{332} = STC_{32}$ / batchsize $= STC_{32} / 55$

$y_{32}^{final} = \lceil y_{32} + ya_{332} \rceil = \lceil 1.2 + 6.59 \rceil = 8$

$SPC_2 = SPC_2 - a_3 \, (y_{32}^{final} - y_{32}) = 56.6$

$PCO_3 = 4.75$, $PCO_4 = 0$, $PCH_3 = 56.6$, $PCH_4 = 51.85$

$STC_{32} = 0$

Update X_{3t}: $X_{33} = 0.2$, $X_{34} = 0.5$

no j^* with $PCS_{jp(j)} > 0$ as $PCS_{13} = PCS_{23} = 0$

$y_{12}^{final} = \lceil y_{12} \rceil = \lceil 1.97 \rceil = 2$

$y_{22}^{final} = \lceil y_{22} \rceil = \lceil 4.32 \rceil = 5$

Update remaining net-requirements X_{it}, $i \notin I_2^*$

week

	3	4
i=1	8.97	5.90
i=2	9.32	7.20

k=3, return to step 1

$k=3 \neq H=4$

$N_3^* = \{1,2,3\}$

$y_{13} = 8.97$, $y_{23} = 9.32$, $y_{33} = 0.2$

$SPC_3 = 57.15$, $SPC_4 = 83.02$, $PCO_4 = 0$, $PCH_4 = 57.15$

$BI_{13} = 1.6$, $BI_{23} = 37.45$, $BI_{33} = 374$

$STC_{13} = 50.05$, $STC_{23} = -5.05$ (overflow because of discrete production

to be taken from safety reserve equalling one batch size, as:

$TC_{wit} = TC_{it}$ - batchsize)

$STC_{33} = 60$

$ya_{143} = 0.91$, $ya_{243} = 0$, $ya_{343} = 0.5$

$PCS_{14} = 0$, $PCS_{24} = 0$, $PCS_{34} = 4$

$i^* = 3$

$I_3^* = \{3\}$

$ya_{343} = X_{34}$

$y_{33} = y_{33} + ya_{343} = 0.2 + 0.5 = 0.7$

$X_{34} = 0$

$SPC_3 = 52.9$, $PCO_4 = 0$, $PCH_4 = 52.9$

$STC_{33} = STC_{33} - ya_{343} * 55 = 60 - 27.5 = 32.5$

$y_{33}^{final} = \lceil y_{33} \rceil = \lceil .7 \rceil = 1$

no more z(3) as we have reached planning horizon H, therefore

$z(3) \not\succ p(3)=4$

no j^* with $PCS_{jp(j)} > 0$ as $PCS_{14} = PCS_{24} = 0$

$y_{13}^{final} = \lceil y_{13} \rceil = \lceil 8.97 \rceil = 9$

$y_{23}^{final} = \lceil y_{23} \rceil = \lceil 9.32 \rceil = 10$

Update remaining X_{it} , $i \notin I_3^*$

	week 4
i=1	5.87
i=2	6.52

k=4, return to step 1

k=4=H

$y_{14}^{final} = \lceil X_{14} \rceil = \lceil 5.87 \rceil = 6$

$y_{24}^{final} = \lceil X_{24} \rceil = \lceil 6.52 \rceil = 7$

$y_{34}^{final} = \lceil X_{34} \rceil = 0$

Stop.

4.3 The production scheduling process:

A) $S_1 = \{$ 1-2-3 , 1-3-2 , 2-1-3 , 2-3-1 , 3-1-2 , 3-2-1 $\}$

S_1	[S_2]	Total switch-over time (in hours)
1-2-3	[3-1-2	9.66
	3-2-1]	11.82
1-3-2	[2-1-3	14.99
	2-3-1]	16
2-1-3	[3-1-2	11.82
	3-2-1]	13.98
2-3-1	[1-2-3	12.83
	1-3-2]	16
3-1-2	[2-1-3	11.82
	2-3-1]	12.83
3-2-1	[1-2-3	11.82
	1-3-2]	14.99

Select 1-2-3 ,3-1-2 with minimal switch-over time of 9.66.

Therefore $\begin{cases} \text{schedule } k=1 \text{ is } 1\text{-}2\text{-}3 \\ \text{schedule } k=2 \text{ is } 3\text{-}1\text{-}2 \end{cases}$

B) k=3

[S_3] = [2-1-3

2-3-1]

	switch-over time
2-1-3	6.99
2-3-1	8

schedule for k=3 is 2-1-3

k=4

$$[\ S_4\ ] = \begin{bmatrix} 3\text{-}1\text{-}2 \\ 3\text{-}2\text{-}1 \end{bmatrix}$$

	switch over time
3-1-2	4.83
3-2-1	6.99

schedule for k=4 is 3-1-2

k=5=H+1 →Stop.

4.4. Summary of final results:

production in batches / week	y_1	y_2	y_3	schedule	switch-over time (hours)
1	9	6	1	1-2-3	4.83
2	2	5	8	3-1-2	4.83
3	9	10	1	2-1-3	6.99
4	6	7	0	3-1-2	4.83
					Total=21.48 hours

5. Conclusions

A heuristic approach to the capacitated single machine lot-sizing problem was formulated, incorporating both production and storage capacities. Also the fact that setup costs are sequence dependent and consume regular production capacity, is taken into consideration. In addition, the batch-nature common to many process industry applications, is incorporated into the analysis.

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